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Highlighting the Dynamical Interaction Between Planets and Planetesimal Belts with ALMA

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Abstract. We observed the debris disk surrounding the young Solar analog HD 107146 using ALMA at 1.25 mm. The continuum emission extends from about 30 to 150 AU from the central star, with a depletion region at intermediate radii (~ 80 AU). The dust density in the outer regions appears similar or larger than in the inner regions, which can be interpreted by models of formation and evolution of planetesimal belts which involve the disruptive collisions of planetesimals triggered by the recent formation of Pluto-sized bodies. If the region with lower dust density at intermediate radii in the disk is a fully depleted gap, then this structure could be carved by a planet with a mass of ~ 1 to few Earth masses at 80 AU from the star.

1. Introduction

Infrared telescopes have discovered hundreds of main-sequence stars where the observed fluxes at mid-infrared wavelengths are brighter than the stellar photosphere (see review by Wyatt 2008). This excess infrared emission is attributed to dust that is produced when planets gravitationally stir a population of planetesimals (asteroids and comets), which subsequently collide and are ground down to dust particles. The dust in these debris disks can be detected in scattered light at optical and near-infrared wavelengths, or in thermal emission in the far-infrared and submillimeter.

Observations at high angular resolution in the submillimeter are crucial to investigate the spatial distribution of the planetesimals in the system. This is because submillimeter light mostly traces particles with sizes of ~ 1 mm, which are virtually insensitive to radiation pressure as well as to Poynting-Robertson drag.

In this contribution we present recent results from our ALMA observations of the debris disk surrounding HD 107146. At a distance of 27.5 pc, HD 107146 has the same spectral type as the Sun (G2V) and a younger age of ≈ 80 – 200 Myr (Moor et al. 2006). Previous Spitzer observations have identified the presence of two components (belts) in the system: a belt of warm dust at ∼ 5 – 15 AU from the star and a colder component at stellar distances > 30 AU (Morales et al. 2011). The cold component was subsequently imaged in scattered light with the Hubble Space Telescope (HST, Ardila et al. 2004; Schneider et al. 2014). These observations revealed a very broad (FWHM ≈ 90 AU) ring centered around ≈ 130 AU.

Its large flux (brightest debris disk around a G-type star) and limited angular diameter on the sky (≈ 12 arcsec) make this disk an ideal target for ALMA observations with high sensitivity and high angular resolution. The disk is also seen as nearly face-on, so that the 2D (radial and azimuthal) distribution of dust can be investigated in detail.

2. ALMA observations of HD 107146

We observed the debris disk around HD 107146 at 1.25 mm with ALMA in Cycle 0. The longest baselines used for the observations were of about 400 m, providing sub-arcsecond angular resolution. Our ALMA observations are an order of magnitude more sensitive and have 2 – 3 times better angular resolution than previous interferometric observations at similar wavelengths with CARMA and the SMA (Corder et al. 2009; Hughes et al. 2011). More information on the characteristics of the observations and data reduction can be found in Ricci et al. (2015).

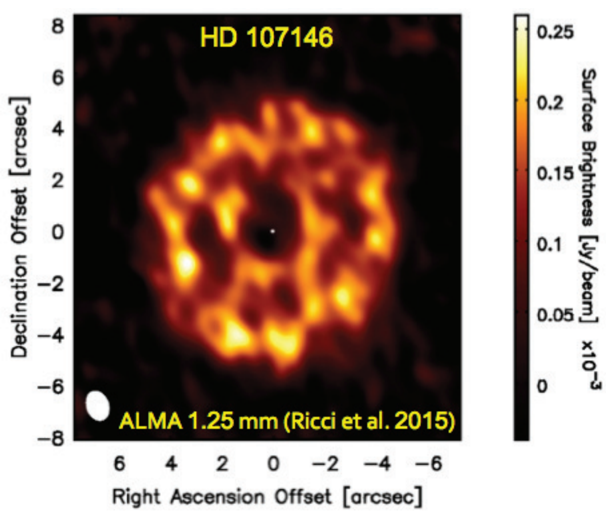

Figure 1. ALMA map of the HD 107146 debris disk at 1.25 mm. The synthesized beam is shown in the lower left corner and has a FWHM size of 1.15″ × 0.84″ (from Ricci et al. 2015).

Figure 1 shows the ALMA map of continuum emission at 1.25 mm obtained after natural weighting the interferometric visibilities. The size of the elliptical beam is 1.15″ × 0.84″, or about 32 × 23 AU at the distance of HD 107146. We measured a flux density from the disk of 12.5 ± 1.3 mJy.

This map shows three main features:

- the dust emission is seen from about 1.5″ to 5″ from the star, or about 30 to 150 AU at the disk distance;
- the surface brightness appears to have a dip toward intermediate radii from the central star. This suggests that the density of particles decreases at those radii;

- the surface brightness has similar values in the inner and outer regions of the disk. Since the temperature is a decreasing function of radius, this indicates that the optical depth in the disk *increases* further from the star.

3. Analysis of the ALMA data

In order to investigate in a quantitative way the physical structure of the HD 107146 debris disk as probed by our ALMA observations we fitted the ALMA interferometric visibilities using models of debris disks. These models consider a debris disk as an axisymmetric, geometrically thin layer of solids, with optically thin emission. The dust temperature was estimated assuming perfect balance between the stellar energy absorbed by grains and the thermal energy emitted by the grains themselves.

For the dust surface density we considered three different classes of radial profiles: *i*) a single power law model truncated at an inner and outer radius, *ii*) a truncated single power law model with the addition of a gap with no dust, *iii*) a truncated double power law model. These specific classes of models were chosen to investigate and quantify the statistical significance of the main features noted on the ALMA image and described in the previous Section.

The power law exponents, as well as the radii describing the inner and outer disk radii, gap and double power law structure were free parameters in the fitting process. We adopted the `emcee` Markov Chain Monte Carlo algorithm[1] to fit the interferometric visibilities and derive probability distribution functions for the free model parameters.

4. Results and Discussion

Figure 2 shows the radial profiles for the dust surface density of each class of model as constrained by our analysis of the ALMA data. The disk inner and outer radii are found at about ≈ 30 and 150 AU, respectively.

For all the three classes of models, the dust surface density is found to be similar or larger than in the disk innermost regions, which is the opposite of what is seen in younger primordial disks. This result is qualitatively consistent with models of the formation and evolution of planetesimal belts in which the formation of Pluto-sized objects trigger disruptive collisions of $\sim 1 - 10$ km sized planetesimals (Kenyon & Bromley 2008, Kennedy & Wyatt 2010). The light seen with ALMA would trace dust generated by recent collisions of these planetesimals, and since the timescale for the formation of Pluto-sized objects increases with radius, this picture is consistent with having denser dust in the outer regions (Ricci et al. 2015, Kenyon & Bromley 2015).

Our analysis also shows that models with a gap and double power law fit the ALMA data *significantly better* than more simple single power law models with no gap. However, the ALMA data cannot discriminate between models with gap and with a double power law. This means that, although a certain level of depletion of dust is seen at around ≈ 80 AU from the star, we cannot yet know the level of depletion as well as the radial profile of dust density in those regions. In the case of a fully depleted region, models of chaotic and crossing zones theory would demand the presence of a planet with a mass of ~ 1 to a few Earth masses to carve a gap in the disk (Ricci et al. 2015).

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[1]For more information see `http://dan.iel.fm/emcee/current/`.

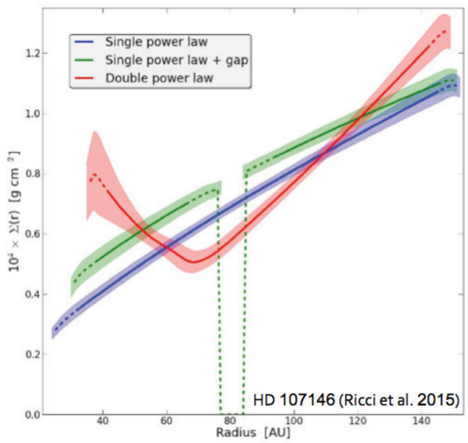

Figure 2. Dust surface density as a function of radius constrained by our analysis of the ALMA data. Thick lines and shadowed regions represent the best-fit model and the areas within $\pm 1\sigma$ from the best-fit, respectively (from Ricci et al. 2015).

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